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Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Evgeny Tsykunov

PhD Program: Engineering Systems

Title of Thesis: Human-swarm interaction for the guidance and deployment of drones using impedance control and tactile feedback

Supervisor: Associate Professor Dzmitry Tsetserukou

The thesis document includes the following changes in answer to the external review process.

The comments from reviewers are numbered and in **bold**. Responses are in non-bold format right after the reviewer comments. Citations from the thesis are indented.

Prof. Youcef-Toumi comments

The thesis considers methods for guidance and deployment of drones using human-swarm interaction, impedance and tactile feedback control. The thesis also considers unstructured environments. Vibrotactile feedback for both guidance and deployment of the swarm of small-scale quadrotors is proposed.

Here are some comments and questions.

1. **The videos are cool!**
   Thank you, we put some efforts into them to make the things a little bit more clear.

2. The abstract needs reorganizing and improving. I suggest you first state the problem, why it is a real problem, its societal impact, corresponding challenges, and technical gaps. Then the approach and proposed solution followed by the thesis contributions.

I updated the abstract in accordance with your suggestions.

3. Check spelling.

I used several different services to check my spelling and grammar. I did it one more time and corrected the mistakes. Hopefully, now it is easier to follow the text.

4. The writing needs improvement. You can start each paragraph with a leading sentence that summarizes the message. The paragraph then provides details to support

the message of the leading sentence. It is important to have the paragraph stay with the message of the leading sentence. This will make your ideas organized and clear.

Every chapter begins with a small summary of the upcoming text. For example Chapter 2:

> In this chapter, we present a comprehensive and critical review of the literature related to the topic of this work. We also define the research gaps in the state-of-the-art. The structure of the information flow is presented in Fig. \ref{fig:backgroud_structure}. We start with some of the autonomy principles behind the swarms. Then we consider the cognitive complexity of the operator and communication approaches. After that, we investigate common control strategies, control input devices, and tactile feedback. Finally, we review possible deployment methods for the UAVs and their limitations.

Many sections also follow the same pattern. I agree with you that each section and subsection need to be started with the leading sentence.

5. Figure 2-7 shows velocity and impedance on the vertical axis with time on the real axis but there seems to be only one trace in dotted line. The units associated with the impedance needs to be corrected.

This is a mistake. Thank you for letting me know. I corrected it. Actually, on the plot there is an example of a goal trajectory generated by a human hand movement, as explained in the thesis text:

> The dynamics of the human control signal can be much faster than the dynamics of the current controlled system. Therefore, track trajectories are not feasible, and the controller of the robot is not able to follow them. The example of the goal trajectory generated by a human operator with the position of his hand is presented in Fig. 2-7. There is no guarantee that the guided vehicle can follow the set points.

6. The text on page 45 says " … shown in Figure 2-11." Without any explanation to what the reader is supposed to see in the figure. It is important to explain to the readers what they are seeing in every figure, table, picture etc…

I agree with the statement that I need to explain every figure in more detail. I corrected the description, as shown below:

> Fig. 2-11 shows the example of a robotic landing gear for a helicopter developed by \cite{Kiefer_2016}. Fig. 2-11 demonstrates how the helicopter performs landing with the usage of landing gear.

7. How are tactile cues used when the number of drones is large?

Developed tactile feedback does not depend on the number of drones in the swarm. Although, we designed the tactile patterns keeping in mind that the number of robots in the formation is large (>100 agents). Under such conditions it is hard to estimate the swarm state in real time using visual feedback. The operator needs to have a certain point of view to understand the swarm behaviour visually. Considering swarms distributed and moving in 3 dimensional space, there is probably no optimal point of view from which it is clearly visible if the swarm extended or contracted. That is the reason why we propose to use tactile feedback to enhance the operator awareness.

To support my point, I provide some text from Chapter 3 Thesis objectives:

> As discussed above in the subsection, to enhance the interaction with the robotics group, the operator has to be aware of the current state of the controlled system. This is hard to achieve when the number of robots is high or when the visual feedback is poor due to the significant distance or communication problems.
>
> ...
>
> We designed tactile feedback to convey information about the formation parameters that are hard to estimate from the visual feedback, i.e., formation state (extension, contraction, and displacement) and state propagation direction (increasing or decreasing drone-to-drone distance). Therefore, tactile cues could effectively supplement the visual channel, making the swarm control more

immersive. Cutaneous feedback could play a key role in enhancing the swarm navigation performance in the unstructured environment, such as cities.

8. Add a paragraph at the end of each chapter summarizing the findings of the chapter.

I already had the summary paragraph at the end of each technical chapter (chapters 4-7). I also added the summary for each of the first three chapters.

9. The intermediate reference frame C is not shown in Figure 4-1 nor defined, as this relates to Equ. (4.1).

I showed the C frame.

10. Equ.(4.5) needs clarification regarding the direction of force Fi and the axis about which the moment Mi is applied.

I clarified this point right after (4.5):

> where force Fi is pointed upwards along z_B direction and moment Mi is also applied about z_B axis.

11. It should be stated that the net force F=u1 in Equ.(4.7) is in the direction of the body axis ZB.

I commented about the u1 after (4.6). I also clarified this point before (4.7):

> We also defined the u1 as a net force acting on the body of quadrotor along the direction of z_B axis

12. The same applies for the moments in Euler's equations.

I commented about the robot body moments after (4.6). But anyway it is better to do it one more time in Euler's equations:

> Robot body moments u2, u3, u4 act along the x_B, y_B, and z_B axis respectively.

13. Fix the subscripts in (4.11)

Sorry for this mistake. Fixed.

14. Why is r assumed small in (4.11)?

I made the description after (4.11) more clear:

> The other typical assumption is that r, which is angular velocity along the z_B axis, in 4.11(a) and 4.11(b) is relatively small, compared to other angular speed components. This assumption is made based on the fact that, during quadrotor motion, the rate of change of yaw angle is typically much smaller compared to the roll and pitch angle changes.

15. Equ.(4.13) is missing "dt" in the integral action term.

Sorry for this mistake. Fixed.4

16. Mismatched parentheses in (4.14).

I fixed them.

17. Section 4.1.3, are there issues with the use of high derivatives? Are these in the measured or the command signals?

Let me clarify Section 4.1.3 Objectives.
By the end of the day we want to achieve smooth behaviour of the controlled quadrotors. In order to have smooth motion of the quadrotor we want the control input to be minimized. From the derived equations of motions and control laws we show the relationship between the control inputs u1, u2, and u3 on one side and the higher order derivatives of the goal position on the other side.
Based on that, we propose to formulate the objective to generate the goal trajectory with minimized higher order derivatives of the position. Basically with our objective we want to affect the control signal generation.
I also updated the thesis text to make it more clear.

18. Equ.(4.16) represents positions. Does orientation play a role in some applications?
That is true. Some applications probably require to have a control under the orientation of the fleet. We relaxed the problem and considered the position only to make the things more simple and clear. For now I believe that the same control principles can be applied (may be with small modifications) to the swarms which orientation also can be controlled by a human operator. We consider it as future work.

19. In the text associated with Figure 4.2 and elsewhere in the thesis, impedance should be Force/velocity.
I agree that I need to keep it more clear. I updated the text.

20. On page 61, define F_ext(t). A schematic of the hand, the primary quadrotor and associated forces and velocities would help in understanding the concept and the notation.
I added the Fig. 4-3 with the human hand, impedance model and controlled drone with proper referencing from the text. Hopefully it will make the things more clear.
All figures below change the numbering.

21. Page 62, what is “impedance link”?
The “impedance link” term will be more clearly defined in the thesis later, in particular in “Proposed Impedance Control Approach for Swarm Guidance” section (basically it is a virtual impedance model inserted between two drones). On page 62 I changed the text and removed “impedance link”:

> In order to calculate the impedance correction term for the robots' goal positions, we solve a second-order differential equation (4.18) that represents the impedance model. To move in three-dimensional space, we have to solve one differential equation for every axis.

22. Equation (4.19) on page 62 is, technically, not in state space form. All differential equations should be 1st order equations. You need to introduce 2 state variables, say position x(t) and velocity v(t).
I introduced two state variables position x(t) and velocity v(t) and updated (4.19-4.21).

23. Starting with equation (4.22), use proper notation to differentiate between the time and frequency domains.
Sorry for this mistake, I corrected the notation.

24. Is u in equ.(4.28) the actuator trust ? also, usually the drag coefficient is unitless. Perhaps you need to explain cd

Yes, u is the actuator thrust, I updated the text to specify this.

Cd in my case is not a drag coefficient in the common convention, but it is a coefficient that incorporates all parameters that contributes to the drag force: area, shape, density, Reynolds number, etc. I stated it out in the text clearly. I used it just to simplify the notation.

25. What is the PID controller on page 65 for? Is it for the simplified model of Figure 4-3?

The whole section 4.3.1 refers to the simplified or "toy problem" of controlling a point of mass shown on the Fig 4-4 (previously Fig. 4-3). I updated the text to keep it more clear:

> Raw trajectory provided to PID controller.
>
> We first feed the goal position of the point of mass from the human to the PID controller directly, without impedance correction. This will help us to see the performance of the controlled point of mass under the simple PID controller. We will use it as a baseline.

26. The text on page 65 and 66 do not show how the hand trajectory goes in the controller, especially Figure 4.5.

I updated the text to clarify this point:

> After demonstrating the performance of the PID controller on step control input, we ask the simulated point of mass to follow a prerecorded position of the human hand. We recorded beforehand the position of the human hand with a Vicon motion capture system (shown in orange line in Fig. 4-6). For this experiment we took the motion in one dimension (the simulated point of mass can move in one dimension). We then sequentially supplied the set positions from the human into the PID controller defined in the previous paragraph. The state of the point of mass calculated based on the (4.28). The resulting trajectory of the position of the simulated object path is presented in Fig. 4-6 in the blue line.

27. Correct units of impedance in Figure 4-6.

Thank you for this update. Actually in Fig. 4-6 (now it is Fig 4-7) there is not an impedance as is, but it is the displacement of the impedance model presented in Fig. 4-2. That is why it is in meters. I corrected the figures and the text.

28. Explain what the reader is supposed to see in Figures 4-6 and 4-7.

Now these figures are 4-7 and 4-8 respectively. I added the explanation to both of them:

> The relationship between the human velocity (as the input to the impedance model) and the impedance correction term (as the output of the impedance model, basically it is the displacement of the impedance model) are demonstrated in Fig. 4-7. It is possible to observe in Fig. 4-7 that the impedance model displacement is smoothed and slightly delayed in comparison to the human velocity.
>
> The integrated set points are demonstrated in Fig. 4-8. In the green color there is the trajectory obtained with the impedance displacement of the model. In comparison to the raw set points (blue line), it is possible to observe that the trajectory with the impedance correction is more smooth and slightly delayed.

29. Page 68, it is not clear how the response was obtained for the 'without impedance' case. It would be better to show how the trajectories and the control inputs were generated.

In the 'without impedance' case we just supplied the raw human hand position as the set point for the controlled object. I updated the text and the Fig. 4-8 subscription to state it more clearly.

30. What is the difference between the impedance control of Figure 4-8a and a conventional filter, say a second order, that takes the hand motion as an input and generates an input for the drone? This is what is often done in robot control, the command is filtered by a 2nd order system before it is sent to the actuator drivers.

The filter actually smooths frequencies. Impedance control has been proposed as the new type of control method when you can change the dynamic parameters of the swarm system. It is possible to change the dynamic behaviour depending on the application. We can change distances between the agents based on the control input and the environment. Yes, along with that impedance control helps to slightly filter the signal, but we use impedance control for more than just filtering. Impedance control is actively used in collaborative robots, please see the DLR works. In our case we use it for safe interaction between the agents within the swarm.

Also, there isn't a clear connection between equ.(4.29) and Figure 4-8a.

There is no direct relationship between them. Eq. (4.29) is for the simplified control problem of the point of mass control. But the common pattern can be seen between (4.29) and (4.30-4.32) - we sum up the goal position coming from the human with the impedance displacement terms.

Finally, how does one deal with the possible change in configuration as the quadrotors fly?

This is the assumption we made in the beginning of the thesis. The default geometrical configuration is predefined and we desire to keep it (I refer to the second term in (4.30-4.32) and term G in (4.34)). Although during guidance, according to the local control laws, for example obstacles avoidance with APF in our case, the geometry can change. But we do not incorporate this directly into the control signal generation. Instead, the obstacle avoidance changes the impedance corrected trajectory, working on top of it (I refer to Fig. 4-10 where obstacle avoidance goes later in the control flow after the goal position calculation in the gray block).

31. Page 69, the text does not explain how the operator pulls or pushes on the virtual mass. Is the operator supposed to feel the interaction with the virtual mass?

I provided the explanation of what I mean by pushing or pulling in the thesis text:

> While the operator is guiding the formation in space, impedance models update the goal positions for each flying robot, which changes the default drone-to-drone distances Lij, for (i,j=1,2,3,4) in our case. As a result, the operator "pushes" or "pulls" virtual masses of inter-robot impedance models, which allows the shape and dynamics of the robotic group to be changed by the human hand movement. Virtual "pushing" or "pulling" of the impedance model mass is achieved with the relationship between the human hand movements and force, which is defined in (4.17). Basically "pushing" or "pulling" is defined with the application of the force in different directions in (4.17).

The operator is supposed to feel the state of the swarm (contraction or extension) via the virtual feedback (will be discussed in the next chapters). The contraction or extension also can be achieved with the virtual impedance models. Therefore, in such a way the operator "feels" the interaction with the virtual impedance models indirectly.

32. Page 71, explain in the text the order Rn2 in G and Imp.

That is true, I need more explanation regarding these terms. Fixed:

> To make the above equations more general, we introduce several terms. Let X_i in R^3 represent the actual position of the center of mass of i_th quadrotor, X_gi in R^3 represent the goal position (that we have to track) of the center of mass of i_th quadrotor, H in R^3 represent the human hand position, G in R^n^2 is a two-dimensional array and represent the default geometry configuration for the vehicles (where n is the number of agents), and Imp in R^n^2 is a two-dimensional array and represent the impedance correction terms (which is the displacements of the impedance models). Geometry configuration G and impedance corrections Imp

express the relationships between the agents within the group. In the most general case we can have some unique relationship between every pair of drones. That is why we propose to represent G and Imp as square matrices with n-by-n size where n is the number of agents. In the less general cases G and Imp can be not full rank matrices with some level of sparsity.

33. Make sure the dimensions in all terms work out in Equ.(4.34) along with the functions f1, f2 and f3, their arguments and their contribution/role to the overall signal.

Thank you for this point. For general form in (4.34) I provide the G and Imp terms for the whole formation or for each pair of agents (n-by-n matrices). That is why I need to correct (4.34) in order to calculate the goal position signal for all agents (not for each agent independently), i.e. the output should have (3 x n) dimension where n is the number of robots. I updated the notation that is supposed to bring the right dimensions.

34. The "quadrotor physical world" of Figure 4-10 contains actuators and sensors. The Figure though implies otherwise. Also, given that the sensors in the yellow bubble include the vicon motion capture system, what do the actuators in the red bubble represent?

I replaced "quadrotor physical world" with the "Environment" in Fig. 4-11 (prev. 4-10). This should fix the issue.

35. What does dynamic stability mean on page 77? What are you referring to?

Sorry for this poor clarification. I updated the title of the section and added the introductory text to clear it out:

Dynamical Stability of the Impedance Models

In this section we consider the selection of the impedance model dynamic parameters M_d, D_d, and K_d to obtain a critically damped response of the system, which we assume to be the most comfortable for the human.

36. What does Figure 4-17 tell us?

I extended the description of Fig. 4-17 (now it is Fig. 4-18):

Fig. 4-18 shows the distance along the Y-axis between Drone 1 and Drone 4, which are placed in accordance with Fig. 4-9(a). The formation is guided along the Y-axis in this case. Zero human hand velocity generates no control input and the default distance between drones is zero. It is possible to see that the distance between Drone 1 and Drone 4 changes in accordance with the human hand velocity, when the human guides the formation in one or another direction along the Y-axis. The bigger gap between drones corresponds to the higher velocity of the control signal, which produces more safe guidance. Fig. 4-19 also presents the area of the formation in projection to the horizontal plane. It is possible to see that the whole area adapts to the control input signals in a compliant manner. It is possible to change the dynamic behaviour of the controlled swarm system by changing the default dynamic parameters of the impedance models and by changing the structure of the impedance links.

37. Are the obstacle locations known or detected/identified automatically in section 4.4?

We consider obstacle detection and localization to be a solved task. In our experiments we used IR markers to detect obstacles with the motion capture system.

38. What are the contributions of the new tactile display prototype, device with eccentric rotating mass (ERM)?

As there is no off-the-shelf wearable tactile display suitable for communication with drones we have developed a novel affordable tactile display that can deliver tactile stimuli to the each finger of the user. The main contribution of the research of SwarmGlove is the designed tactile patterns for effective communication with the swarm. The experimental results reviewed patterns which are easier to discriminate by the user.

39. Why is Figure 5-2a is labelled "contracted state" for the case with increasing distance? Contract means a decrease in size! Is it to decrease the size of the configuration?

Let me explain the terminology that I have used here. Probably it is not the best from the linguistic point of view, but what is more important - I want you to understand the concept. Based on the actual distance between the agents we determine the following three states:

- Contracted (distances small)
- Regular (distances default)
- Extended (distances large)

We call the above three states - static states.

In parallel to the static states we define dynamic states. Dynamic states are defined based on the rate of change of the drone-to-drone distance. There are three of them:

- When distance increasing
- When distance decreasing
- When distance remains constant

Dynamic states do not depend on the static ones. Therefore, while being in a contracted state, the distances can increase or decrease.

40. What happens when the drones end up moving in different directions?

Actually this is the case of increasing distance - this is a type of dynamic state (represented by patterns in Fig. 5-3(b, d, f)).

41. It is not clear from the text where the input to the ERMs come from?

I refer to the 5.1.1 section:

> We have designed a tactile display prototype with five ERM vibrotactile actuators attached to the fingertips, as shown in Fig. 5-1(a). The vibration motors receive control signals from an Arduino UNO controller. The unit with Arduino UNO and battery is worn on the wrist as a portable device. Infrared reflective markers are located on the top of the unit. The frequency of vibration motors is changed according to the applied voltage. The haptic device diagram is shown in Fig. 5-1(b). The glove microcontroller receives values of the formation state parameters from the PC. The Bluetooth and USB communications between the computer and haptic device were presented in the previous research Tsetserukou et al. 2014. The approach in Tsetserukou et al. 2014 is limited in working distance and mobility. We implemented a radio frequency connection through XBee Pro s2b radio modules due to its robustness and high speed of data exchange. After the Arduino UNO gets the information about the current swarm state, it applies an appropriate vibration pattern.

42. What is the effect of sustained vibrations on the operator?

We discussed the issue and the solution to the sustained vibrations in section 6.6.2. Sustained vibrations cause masking factor. Basically the solution is the time delays between the patterns. We discuss it below in section 6.6.2:

> The performance of the multimodal tactile patterns is limited by the masking factor as reported in the literature by \cite{Evans_1987} and by \cite{Tan_2003}. The problem of masking is revealed when the one tactile stimulus is immediately followed by the other without any time gap. It turns out that the human is not able

to distinguish and recognize any of them. That is the reason why we introduced time delays between the tactile patterns and separate tactile stimulus.
As an outcome, the main limitation is that we are not able to increase the density or rate of the information provided with the tactile feedback. Information flow rate is asymptotically limited with the masking factor. Therefore, the awareness of the human operator about the swarm dynamics is also limited.

43. Why is the recognition rate about 77%? What limits it?

I refer to section 5.2.3 where I discussed the results of the tactile pattern recognition. I also discussed in section 5.2.3 the reasons for the revealed recognition rates. In addition I can add that basically the recognition rate is limited by the number of information that we want to deliver to the human. The more patterns we have - the more similar the patterns to each other and it is harder to distinguish between them and remember them. To support it I also refer to section 6.6.2, where I discuss the number of information that we want to deliver to the operator.

44. What are the implications of the long response times in Table 5.2?

Based on response time (reported in Table 5.2) we selected the information that we want to deliver to the human operator during guidance.
To answer this question I refer to Section 6.2.

> The next decision we made was about the parameters of the fleet that have to be reported to the human operator through the tactile interface. As discussed before, for the flight experiment, we use small quadrotors and limited flight space. In such an operational condition, change of the formation shape (increasing or decreasing drone-to-drone distance) could happen quickly. Therefore, it is inefficient to provide slow tactile feedback (see Table 5.2) about it.
> On the other hand, contracted (Fig. 6-2(a)) or extended (Fig. 6-2(b)) state of the fleet could last for seconds, which makes them applicable candidates for the flight verification.

I also discussed the limitation of the slow tactile feedback in Section 5.3 “Generalization to Other Types of Robotic Systems”.

45. What are the issues associated with a larger number of drones?

I have the whole section 8.3 “Scalability of Guidance Methods” that discusses the bigger number of drones along with rising limitations and challenges.

46. I suggest you add additional description on the flow of information and interaction between the hand and the drones, etc..

Fig. 6-1 presents the general diagram (with information flow) for the interaction between the operator and the drones. I provided more details into the description of this figure:

> We already presented a general overview of the interface in Fig. 1-3. In Fig. 6-1 we show a more detailed picture of the interface that we developed with all the components (impedance control, obstacle avoidance, tactile display, and tactile feedback). The information flow is the following. Formation of drones flies in the environment. State of the fleet can be changed due to control signals from the human or based on local control laws (drone-to-drone or drone-to-obstacle avoidance). The human is becoming aware about the state of the formation with the help of tactile feedback. Based on the information about the guided fleet of robots the operator generates the control signal with a glove, which in turn changes the formation state. This is a general overview of the interaction loop.

In the case you are interested in the more detailed information regarding the information flow, I refer to Fig. 4-12 Overall control system architecture.

47. Figure 6-1 does not show that there is an impedance control between the drones as was indicated in earlier chapter.

It is there. In the control signal flow coming from the human operator there is an impedance control part. This impedance control part incorporates all architecture shown in Fig. 4-9(a). This is how we show impedance control in Fig. 6-1, that we discussed in Chapter 4.

48. How to reduce the differences (right most column) in Table 6.1?

To be more specific in this discussion, let's consider the case we implemented during the experiment, discussed in Section 6.4. To approach the visual feedback:

1. Tactile feedback has to be faster. It takes time to execute a tactile pattern and it also takes time for the human to recognize some complex pattern. In addition we are limited with a masking factor (we have to introduce a time delay between tactile stimulations to make them distinguishable). Solution: shorter in time and simpler tactile patterns.
2. Tactile feedback has to be more informative, i.e. we need more informative tactile patterns or just the bigger number of them.

Obviously there is a trade off between points 1 and 2.

3. Tactile feedback has to be present if the visual feedback is poor or unstable. It is easy to overperform visual feedback if its quality is bad. That can be the case when the point of view of the operator is not the best or when the visual signal received by the operator is bad quality. Tactile feedback requires much less bandwidth of the information flow and therefore more reliable for the transmission to the operator.

49. The maze trajectories using tactile are more random with much more time than the visual ones in Figure 6-7!

That is fair observation. We discuss it at the end of the 6.5 section. Pure tactile feedback leads to more active space exploration and therefore it looks more random. On average, visual feedback leads to 4.5 times faster guidance than tactile feedback. Which is an obvious result because the vast majority of information that the human receives from the environment comes with vision and as a result it is the most convenient feedback type especially when the controlled drones are right in front of the operator.

50. The text does not provide enough information about how the tactile/impedance etc. control were implemented in chapter 6.

We covered most of the technical details along with the implementation specifics in the separate Chapters 4 and 5. We basically apply exactly the same implementation in Chapter 6 for the experimental validation. According to the beginning of the Chapter 6:

> In the previous Chapters 4 and 5, we developed the control methods and wearable tactile display for the swarm state feedback. Both control and feedback form the communication interface between the human operator and the swarm system. In the current chapter, we present the evaluation methodology and the experimental results of the guidance methods presented in the previous chapters.

51. There is no apparent discussion of the dynamic behavior between drones, especially the proposed impedance control.

I refer to Chapter 4 to answer this question. The whole chapter basically related to the impedance control and how it is used for the interaction. After the control objective specification I derived the math behind the applied impedance control. Then I validated the proposed methods on the simplified toy problem, then on the real single drone and finally on the formation of real four drones. I also demonstrated how the drone-to-drone interaction was affected by the proposed impedance control in Fig. 4-18 and Fig. 4-19 (where distances between drones and formation area is visualized).

I also refer to Section 8 where I discuss "Scalability of Guidance Methods".

52. How does the human operator keep up with rapid changes in the drone configuration while performing the control?

Fleet is following the human with impedance control and therefore there is some delay. It increases safety of human-drone and drone-drone interaction. In general, in the case of PID control the response of drones is faster. Regarding the feedback, of course there is the limitation of the tactile feedback in terms of the information rate it is able to deliver to the human, we discussed before in this document (question 44 for example).

53. Did the subjects comment on the effectiveness of the tactile approach versus the visual especially while controlling the drones through obstacles?

Let me start with a reference to the Section 6.5 Flight experiment results:

> As discussed in Section 6.1, for the current experimental conditions (when the controlled system right in front of the human and the operation space is small), performance with visual feedback is better than with tactile feedback. Which is an obvious result because the vast majority of information that the human receives from the environment comes with vision and as a result it is the most convenient feedback type, especially when the controlled drones are right in front of the operator.

Based on that, it is obvious that for the users the visual feedback was better and more informative. But I provided an extended discussion of what can be learned from the available experimental facilities in the beginning of Chapter 6. One of the main outcomes is that tactile feedback can work as a standalone feedback type with acceptable performance metrics.

54. It seems that the results show that the visual approach generally provides better performance. I would assume that this will be the case for the large-scale case. So it is important to state when the tactile approach is applicable or preferred.

During the large-scale case the visual feedback can suffer from some unexpected reasons (discussed before: wrong point of view, bad connection for visual signal transmission, etc.). That is the main application that we see for the provided guidance methods with tactile feedback. Regarding the results of the experiments - I refer to the previous question - 53. It is obvious that when the controlled drones right in front of the operator (the distance is several meters) the visual feedback wins. But in spite of that, we tried to measure some metrics and extrapolate the results to the bigger number of drones and large distances.

Prof. Ivanov comments

1. **Pg 45 (Figure 2.11) explain picture 2.11 in more detail. What are we looking for in the picture?**

   I present the picture in order to show that the adaptive landing gear is the complex structure that is not lightweight. I updated the text:

   > Fig. 2-11 shows the example of a robotic landing gear for a helicopter developed by Kiefer et al. 2016. Fig. 2-11 demonstrates how the helicopter performs landing

with the usage of an adaptive landing gear. Landing gear represents a mechanical system with moving joints, which contributes to the additional weight of the system.

2. **Pg 46 (sect 2.7) may be this summary can be improved a bit to show reasoning for selecting tech for this particular research. simple table might do it.**
   I updated the summary in Section 2.7:

   > In this chapter, we presented an existing research related to the topic of this work. We also defined the research gaps.
   > We covered the existing control methods which is topically used for the swarm of drones operation. The literature review revealed that generation of control signals and the swarm response to the control commands are crucial parts of the control strategy. The state of the art control strategy for drones is the PID controller (when the drones strictly following the corresponding goal positions). It works well until the human is involved in the direct control of the robotic formation. Various disturbances can happen in this case because the human is not able to generate dynamically feasible control signals. Reviewing state-of-the art, no strategy considers the adaptive behavior of the guided fleet of micro-quadrotors, helping to get a smooth and safe response of the robots in various conditions. Along with that, we showed that impedance control is widely used in industrial manipulators and humanoid robotics to ensure safe interaction between the robot and the environment.
   > Apart from that we considered the haptic feedback that is used for the interaction of a human with robotic systems. To enhance the interaction with the robotics group, the operator has to be aware of the current state of the controlled system. For example, the operator needs to know if the fleet is split into two groups while avoiding obstacle or if the team is squeezed and drone-to-drone distances is decreasing. This is hard to achieve when the number of robots is high or when the visual feedback is poor due to the significant distance or communication problems. We hypothesize that the tactile feedback can enhance or even sometimes fully replace the visual feedback.
   > Finally we discussed the deployment challenges and existing solutions along with its limitations. To complete a flight mission, the swarm of drones has to take off in the beginning and land in the end. Many crashes happening during these stages that is why we consider it as an important part of HSI. Adaptive landing gears substitute the landing and takeoff operations on the uneven surfaces. The problem is that, due to the lack of payload abilities of micro-quadrotors, it is almost impossible to carry the adaptive landing gear or significant computational power that can help to land. Up until now, no technology safely lands multiple micro-quadrotors on the uneven surface in the unprepared environment.

3. **Pg. 70 Figure 4.9 Subscript “h” is stands for Human.**
   I fixed the issue.

4. **Pg. 112 (sect 6.5) how the obstacle information is transmitted back to user? I’m sure it is written somewhere, but I didn’t manage to find it.**
   The information about the obstacles are not delivered to the human directly. I refer to the section 3.2.2 to support my answer:

   > It is often easier to estimate the parameters of the whole robotic group (e.g., dimensions, velocity) rather than map all the drones' environments. The main novelty is that we propose to deliver tactile feedback about the state of the swarm rather than about the distance to obstacles or the desired direction of motion. We designed tactile feedback to convey information about the formation parameters that are hard to estimate from the visual feedback, i.e., formation state (extension, contraction, and displacement) and state propagation direction (increasing or decreasing drone-to-drone distance).

5. **Pg. 139 It is mentioned above, but I will repeat it here as well. In this work, the experiments are performed in an outdoors environment not described and some reflection should be done on how quality of outdoors signals will affect control. Impedance based control methods can be used outdoors (although not with microdrones), rapid feedback using tactile sensation can improve precision of maneuvering, given sufficient training of the operator.**
   We initially we have been motivated by the outdoor applications. To answer this question, I refer to the page 143 (section 8.3, Scalability of Guidance Methods) where I discuss the possible application of the developed approached for the outdoor environment. Basically, you are right. Some limitations will rise in comparison with the indoor experiments, but many of them can be solved.